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(54) Title: APPARATUS AND METHOD FOR AUTOMATIC RECOGNITION OF CONCEALED OBJECTS USING MULTIPLE ENERGY COMPUTED TOMOGRAPHY

(57) Abstract

An apparatus and method for automatic recognition of concealed objects and features thereof, such as contraband in baggage or defects in articles of manufacture, is disclosed. The apparatus uses multiple energy x-ray scanning to identify targets with a spectral response corresponding to a known response of targets of interest. Detection sensitivity for both automatic detection and manual inspection are improved through the multiple-energy, multispectral technique. Multichannel processing is used to achieve high throughput capability. Target identification may be verified through further analysis of such attributes as shape, texture, and context of the scan data. The apparatus may use a statistical analysis to predict the confidence level of a particular target identification. A radiograph, CT image, or both may be reconstructed and displayed on a computer monitor for visual analysis by an operator. Finally, the apparatus may receive and store input from the operator for use in subsequent target identification.

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APPARATUS AND METHOD FOR AUTOMATIC RECOGNITION OF CONCEALED OBJECTS USING MULTIPLE ENERGY COMPUTED TOMOGRAPHY

GOVERNMENT INTEREST

The invention described herein may be manufactured, used and licensed by or for the government for governmental purposes.

BRIEF DESCRIPTION OF THE INVENTION

The present invention relates generally to the field of nondestructive inspection. More particularly, the present invention relates to an apparatus and method for detecting concealed objects and features thereof, such as contraband in baggage or defects in articles of manufacture, using multiple energy computed tomography.

BACKGROUND OF THE INVENTION

Conventional x-ray scanning is used in a number of fields to detect objects or features not visible to the human eye. For example, in the medical and dental fields, x-ray systems are used to detect features of interest in rendering a clinical diagnosis, such as a fractured bone or a cavity. In the manufacturing industry, x-ray systems are used similarly to inspect parts for defects. Fractures or voids below the surface of a weld, for example, can be detected from an x-ray image, thus avoiding possible failure of the part should it be used in its defective condition. X-ray systems are also used in airports and other public facilities to inspect containers for weapons, explosives, and other contraband.

In each of the foregoing applications, the x-ray system is merely an imaging device without the capability of automatic identification of targets. These systems produce a gray scale image, representing the total x-ray energy absorbed by all objects between the x-ray source and the image plane: the more energy absorbed, the darker the corresponding spot on the image. Using this projection method, the resulting images or radiographs are often difficult to interpret because objects are superimposed. Data obtained from x-ray images are generally unsuitable for automatic detection because of the complexity involved in resolving superimposed objects. A trained operator must carefully study and interpret each image to render an opinion on whether or not a target of interest is present. Where an application requires a large number of radiographs to be interpreted, operator fatigue and distraction can compromise detection capability.

X-ray Computed Tomography (CT) is a technique that produces an image of a cross-sectional slice of an object from a series of attenuation measurements taken at various angles

around the object. The CT image does not suffer from the superpositioning problem presented with standard radiographs. Although CT data can provide precise, quantitative information about the characteristics of objects in the scan plane suitable for automatic detection of targets, it too has limitations. Conventional CT systems take considerable time to perform a scan, to capture the data and reconstruct an image. Throughput of CT systems is low. Coupled with the size and expense of conventional CT systems, this limitation has hindered CT use in applications such as baggage or parts inspection where object throughput is a major concern.

U.S. Patent 5,367,552 to Peschmann (1994) teaches one method for improved CT throughput. In the Peschmann system a conventional x-ray scanner is first used to pre-scan an object, followed by CT scanning at locations selected from analysis of the pre-scan data. Although the solution taught by Peschmann provides improved detection capability over conventional x-ray systems, it has several limitations. First, it requires pre-scanning of the object with a conventional x-ray system which takes time and provides limited results as discussed above. Second, in order to save time, a CT scan is performed only at selected locations which could result in failure to identify targets of interest, especially where the target is masked or otherwise difficult to detect with a conventional x-ray scanner. Third, because the Peschmann invention uses a conventional rotating CT device, the throughput is limited by the mechanics of the rotation. Fourth, the baggage is stopped, again limiting throughput, to allow for rotation of the x-ray source around the object at each slice. Finally, Peschmann teaches the use of conventional single- and dual-energy techniques for generating CT data whereas a multiple-energy or multispectral technique as described herein would result in improved target identification.

OBJECTS AND SUMMARY OF THE INVENTION

Accordingly, the objects of the present invention are as follows:

(a) to provide automatic recognition of concealed objects and features thereof with or without operator involvement;

(b) to detect small quantities or features of a target of interest concealed within an object;

(c) to allow for high throughput of objects during scanning operations without compromising detection capability;

(d) to provide CT data using a compact stationary x-ray source array and detector array;

(e) to provide an enhanced x-ray image or CT image or both for operator viewing;

(f) to provide statistically based confidence levels for target identification; and

(g) to provide a continuous learning capability for improving target identification with system use.

These and other objectives are achieved by an apparatus and method for automatic recognition of concealed objects. The apparatus uses multiple energy x-ray scanning to identify targets with a spectral response corresponding to a known response of targets of interest. Detection sensitivity for both automatic detection and manual inspection are improved through the multiple-energy, multispectral technique. Multichannel processing is used to achieve high throughput capability. Target identification may be verified through further analysis of such attributes as shape, texture, and context of the scan data. The apparatus may use a statistical analysis to predict the confidence level of a particular target identification. A radiograph, CT image, or both may be reconstructed and displayed on a computer monitor for visual analysis by an operator. Finally, the apparatus may receive and store input from the operator for use in subsequent target identification.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of the individual hardware components of the present invention, with their logical connections.

FIG. 2 is a schematic representation of one embodiment of the present invention for baggage inspection.

FIG. 3 is a schematic representation of another embodiment of the source and detector elements of the present invention.

FIG. 4 is a schematic representation of another embodiment of the present invention for inspection of manufactured parts.

FIG. 5 is a flow chart depicting the major steps in carrying out the present invention.

FIG. 6 is a flow chart depicting the major processing steps on the present invention for analyzing multispectral data.

FIG. 7 is an illustration depicting the use of multispectral data to produce an enhanced image.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1, an apparatus in accordance with the present invention is depicted. By way of overview, the apparatus is first described by reference to its major components. In this particular embodiment, source array 1 is an L-shaped support member comprised of several x-ray sources spaced along its length. The individual x-ray sources, as illustrated by source 12-15 in

FIG. 1, provide a series of co-planar fan beams 16-19 in response to a signal from controller 6. Each fan beam 16-19 is comprised of x-ray photons of varying energy levels within a fixed energy band. Source array 1 is positioned opposite to and separated from detector array 2 to form a space within which object 21 may be scanned.

Detector array 2 is also L-shaped in this particular embodiment and is comprised of individual detector elements 20, which are arranged at regularly spaced intervals along its length. Detector element 20 absorbs the photons from source array 1 and provides a voltage signal to data acquisition circuit 3. The resulting voltage signal is proportional to the energy level of the photon absorbed by detection element 20 after traveling along the beam path from source array 1 to detector array 2. By using a series of separate detector elements 20, the position along detector array 2 where the photon was absorbed can be determined and correlated to the corresponding energy measurement. The spatial resolution of the resulting x-ray scan data is thus determined by the size and spacing of detector elements 20. Very small detector elements 20 closely arranged and abutted against one another along array 2 will provide precise information as to where a photon energy measurement was taken. Such a configuration, however, requires a large quantity of elements 20 to fill the length of array 2 and a correspondingly large number of data acquisition circuits 3, as described below, to capture and process the resulting data. Thus, an analysis of the required spatial resolution versus component cost should be made to determine the optimal size and spacing of detector elements 20 along array 2.

A multichannel data acquisition circuit 3 is provided for rapid processing of the voltage signals from detector elements 20. Each channel of circuit 3 is electrically coupled to one detector element 20 and is comprised of a detection processor 11 and a series of comparators 9 and counters 10. Detection processor 11 provides a separate voltage threshold signal to each comparator 30-34 for comparison with the voltage signal from detector element 20. As more fully described below, data acquisition circuit 3 forms spectral attenuation data, defined as the number of photons absorbed by each detector element 20 versus the energy level of the absorbed photons, from the analog voltage signals provided by detection element 20. These spectral attenuation data are provided to processor 4 at specified intervals for further processing.

Processor 4 is a computer processor with parallel processing capability. Each channel of data acquisition circuit 3 is electrically coupled to processor 4 for input of spectral attenuation data. Processor 4, using CT reconstruction algorithms, reconstructs from the spectral attenuation data a tomographic image of the cross-sectional slice of object 20 which was scanned to acquire the data. A pixel in a tomographic image of a cross-sectional slice is called a voxel because it represents material in a volume element whose dimensions are those of the pixel and the

thickness of the slice. The raw x-ray image data are also preserved by processor 4 for subsequent display using interface 7. In the present invention, the CT reconstruction algorithm is applied to each of the five measured attenuation data sets resulting in multiple-energy CT data. As more fully described below, these data are used to enhance the signal-to-noise ratio of the CT image data. The resulting CT image data are then matched with the data from file server 5, which represents known targets of interest. Objects or features of interest that are concealed within object space 21 are thus automatically identified. Selected tomographic images and raw data are also stored on file server 5 for later reference.

Tagging system 8 is provided in this particular embodiment for applying an identification tag to object 21 in response to a signal from controller 6 when a positive target identification is made by the apparatus. A defective part or baggage that contains contraband is thus tagged for subsequent human attention. In an alternative embodiment, an automatic sorting and materials handling system may be used to automatically separate defective parts from nondefective parts.

User interface 7 is provided to display enhanced x-ray and CT image data for human viewing and to receive input from a human operator. Interface 7 is electrically coupled to controller 6 for sending and receiving data. Interface 7 also is used to download selected images from file server 5 for display to the human operator. X-ray and CT images may be enhanced by, for example, using different colors to represent different groups of attenuation spectra and a unique color for targets of interest. In the preferred embodiment, interface 7 is a large, high-resolution color touchscreen for ease of viewing and input operation.

Having provided a general overview of the major components, attention is now turned to a more detailed operational description. Depending upon the particular application, a conveyor belt or other means is provided to move object 21 forward through the space defined by source array 1 and detector array 2 for scanning. As object 21 is moved forward, each of the x-ray sources 12-15 is activated in sequence by controller 6 such that only one x-ray beam 16-19 is produced at any one instant. The path of a particular photon that caused a voltage signal to be emitted from a detector element 20 can thus be determined from the known position of source 12-15 from which it was emitted and the known position of the detector element 20 at which its energy level was measured.

By way of example, x-ray source 12 is activated first, emitting a continuum of energy photons of known spectral content up to some known energy level to form a fan beam 16, part of which passes through site 22 in object 21. As each photon is absorbed by detector element 20, a voltage signal in proportion to the energy level of the photon is provided to circuit 3 by the detector element. The voltage signal is provided as a first input signal to each of the five

comparators 30-34. Each comparator 30-34 receives a second input signal from detection controller 11 for use as a threshold voltage. When the input voltage from element 20 exceeds the threshold voltage from controller 11, a counter 35-39 is incremented by one unit. For example, when the input voltage of comparator 30 exceeds the threshold voltage from controller 11, counter 35 is incremented by one unit. Comparators 30-34 and counters 35-39 function in the same manner to count the number of times a threshold voltage is exceeded. In this manner the total count in counter 35 accumulated while source 12 is active represents the intensity of spectral range above the comparator threshold. Intensity of multiple spectral ranges are thus formed by setting the voltage thresholds of comparators 30-34 at different levels. After a brief period of time, x-ray source 12 is deactivated by controller 6, the contents of counters 35-39 are loaded into processor 4, and the counters are reset to zero in response to a signal from controller 6 via detection controller 11. X-ray source 13 is then activated by controller 6 and the detection, data acquisition, and processing steps described above are repeated using source 13, followed by source 14, and finally, source 15. Double buffering is employed between counters and controller 6 for greater throughput. The counter data are sent to processor 4 for the period during which each of the x-ray sources was activated is sufficient to calculate one set of tomographic images.

The use of a parallel data acquisition circuit 3 for each detector element 20, increases the processing speed of the apparatus so as to limit the amount of time needed to activate source 12 and collect the resulting attenuation data. In this way, object 21 may be moved continuously through the apparatus during scanning operations while still providing sufficient data for automatic target identification. Parallel data acquisition is made practical through use of Application Specific Integrated Chips (ASIC) for circuit 3. Data acquisition circuit 3 also provides for field adjustment of the selected energy ranges.

An alternative energy resolving method would be to send the photon signal to an analog to digital converter (ADC) followed by digital binning. For a limited number of bins the first embodiment is faster, cheaper, and preferred because digital processing is avoided and energy discrimination is done in the analog mode. If the number of bins were increased to several hundred, then multiple ADCs would be more practical.

As fan beam 16 passes through object 21, some of the photons of beam 16 are absorbed by the material at site 22 within object space 21, some photons pass through unaffected, and some photons are scattered showing up as lower energy photons. In that the path of scattered photons is unknown, they are a source of noise. A collimator placed in front of detector element 20 decreases the portion of scattered photons impinging the detector element. The number of photons absorbed compared to the number of unaffected photons, that is the attenuation of the x-

rays, is a function of the energy of the photons and the type of material at site 22 through which it passed. In general, the number of photons of any energy range impinging on detector element 20 will be less after passing through the material of object 21 than would have been if no material were present. In as much as the proportional decrease in number of photons of different energy is a function of the chemical composition of the material, the ratios representing the proportional decrease can be used to characterize the material. By using sources 12-15 having a continuum of energy, and capturing the resulting multi-energy spectrum after the photons have traveled through object 21, and comparing that passing through material at site 22 to that which would be captured with no material present at site 22, additional data are provided about the chemical composition of object 21 over systems that use a single- or dual-energy technique. Used in conjunction with other image processing means, such as described below, this multispectral data provides for greater discernment of contraband in baggage, defects in articles of manufacture, and similar applications.

Processor 4 is used to separate the counter values by spectral range and to calculate a tomographic image for each spectral range. Attenuation of the x-rays by the material at site 22 is contained in the data acquired from those detector elements which acquired x-rays passing through site 22. Tomographic reconstruction of the voxel at site 22 is performed by appropriate mathematical combination of the data. For the geometric configuration of the x-ray source and x-ray detector of figure 1 the algebraic reconstruction technique is most appropriate for calculating the tomographic image. For other geometries other reconstruction techniques may be more appropriate. Since the differing spectral data were acquired by the same detector elements 20 at the same time, the voxels in the respective spectrally differing tomographic images are also coincident. The set of values for the five spectral ranges for any one voxel site 22 is endemic of the actual spectral attenuation occurring at that voxel and can be used for characterizing the material at the voxel site. For object 21 in continuous motion while attenuation data are acquired by detector elements 20, the scan is helical and the tomographic reconstruction is a type of helical tomographic reconstruction. Processor 4 after calculating the values stores the values onto file server 5 for later reference.

Processor 4 fits the spectral values of each voxel to that of various known target values stored on file server 5. From the comparison a coded image is constructed which exemplifies voxel-by-voxel the most probable materials and the degree of probability. For some cases the effect of certain artifacts in the reconstructed image can be reduced by calculating a new set of images from the difference in the values of the respective voxels in the respective spectral images. In that case the difference images are fit to target values instead of the spectral images

themselves to construct a coded image which exemplifies voxel-by-voxel the most probable materials and the degree of probability. Processor 4 performs an analysis on the coded images by looking for groupings of neighboring voxels whose composition is nearly the same. Processor 4 compares the grouping size and shape to that of the probable material to further uniquely identify the object. Processor 4 may be used to perform other analyses to measure or calculate unique parameters which are known to increase the probability of recognizing objects. The data can be Fourier transformed and a spatial frequency characterization made. The data, for example, can be wavelet transformed to enhance finding object shapes. Characteristics such as 3-dimensional roundness, granularity or texture can be measured. These and other data processing techniques are well known in the art and may be practiced with the present invention for certain applications. The final result of this data analysis can be either a decision on whether a particular feature was detected, or can be an enhanced image for human viewing, or both.

Because x-ray systems can drift considerably from the desired calibration state, the present invention also includes means for reducing this problem. A gross calibration factor can be added in real-time to the overall system using processor 6 along with a standard in the field of view. In this way, a general calibration correction is applied to all of the detector elements 20. The calibration drift problem is also reduced in the present invention through the use of relative absorption values, which serve to increase the signal-to-noise ratio of the data as described below.

Tagging system 8 is used in one embodiment to automatically tag a container or part when a positive identification is made. An alternative embodiment could include an automatic sorting and material handling system in place of tagging system 8. User interface 7 is used to both display the results for human viewing and to receive input from the operator. Initial calibration of the system can be achieved using interface 7 to input the correct response for scan objects of known content. The same feature can be used for continuous improvement of the system.

Continuous improvement is performed by a self-learning method provided for in the system. Objects 21 of known material and identification are scanned by the system. The system in performing its feature discerning operations will find voxels of like material, group the voxels into shapes, calculate parameters characterizing shape, size, and texture even though the new object does not correlate to any known object. The operator groups the calculated parameters and tells the system to add the new set of parameters to its list of known objects. The system now includes the new object in its matching for automatic detection.

Having provided a general overview of the present invention, attention is turned to a more detailed description of suitable physical components for certain applications. FIG. 2 is a schematic representation of one embodiment of the invention as developed to meet the specific needs of a particular baggage inspection application. In this application, baggage throughput as well as system cost and size are major concerns. The system must function at normal baggage handling rates (up to 2 feet per second), fit in a limited space, and must be compatible with existing baggage handling equipment. This is accomplished with the apparatus illustrated in FIG. 2. An array of x-ray sources 40 and photon energy absorbing detectors 41 are arranged in a vertical plane between the ends of two conveyor belts such that a bag moving from one belt to the other will come between the x-ray source array 40 and detector array 41. The spacing of sources and detectors provide multiple beam paths, which allow for computed tomography with no moving parts within the apparatus. Conventional CT systems move the x-ray source, the detector array, or both to achieve similar results. Although other arrangements can be used, the square geometry of the source and detector arrays provides sufficient room for baggage to pass through, while minimizing space requirements for the apparatus. Linear and relatively short components allow for a modular design that can be adapted to various geometries. The arrays 40 and 41 are located at a gap in the conveyor system to reduce signal interference from the conveyor hardware. Finally, the system may be designed such that it can be scaled geometrically in size and resolution while still employing the same mathematical analysis and using the same basic components. In this way, systems can be easily customized for a particular application without a huge design effort.

FIG. 3 is a schematic representation of another embodiment of the source and detector elements suitable for an application where the size of the apparatus is not a major concern. In this embodiment, the source array 52 and detector array 50 are configured as two concentric rings of equal diameter with the counterpoint of one array offset longitudinally a short distance from the counterpoint of the other. The distance between source array 52 and detector array 50 is exaggerated in FIG. 3 to illustrate the configuration of each ring. This geometry has the advantage of broader coverage for each source in comparison with the first embodiment of FIG. 2 because of the larger distance between source and object. Also, the scan space is evenly covered by x-ray beams in this embodiment because of its symmetry. The major disadvantage of this embodiment is that it occupies more space than the L-shaped arrays of FIG. 2. It also lacks the modular design of the first embodiment, however, a circular array could be approximated with a series of linear arrays to form a polygonal shape. In this way, a modular design can be

achieved that approximated the circular shape of FIG. 3 while reducing component replacement costs.

In other applications, particularly the manufacturing arts, the object to be scanned may be uniform in shape, composition, or both. True tomography may be replaced with pseudo tomography by employing a priori knowledge of manufactured components--their geometry, position, and material composition--as constraints in the reconstruction. In such situations, reduced system cost and faster computational speed can be achieved using a source and detector embodiment as illustrated in FIG. 4. Here, two sources 60 and 61 are used with two detector planes 62 and 63. Although greatly simplified in comparison to the other embodiments of FIG. 1-3, the techniques of the present invention can be used in this and similar embodiments.

Having provided an overview of suitable hardware elements to be used in accordance with the present invention, attention presently turns to the processing steps to be executed on the hardware. Turning to FIG. 5, the major steps in carrying out the present invention are illustrated as a flowchart. The process begins with initiation of the source number to one in step 80. The source is activated in step 81 to generate a beam of photons directed towards the object to be scanned. The energy level of the photons after traveling along the beam path is then measured in step 82. In step 83 spectral data are formed from the measured energy levels by counting the number of photons within a certain energy range absorbed by each detector during a specific time increment. In step 84 the source number is checked to determine if all sources have been activated. If not, process step 88 is performed to increment the source number and return to step 81. If all sources have been activated, then process step 85 is performed to analyze the spectral data. In this way, steps 81-83 are repeated for each x-ray source.

The results from the above steps are used to form and analyze multispectral CT data in step 85 as discussed fully below. These data are then compared to data representing known targets of interest in step 86 to determine if one or more targets of interest are present. If not, an appropriate message is displayed in step 89 along with an enhanced x-ray or CT image for operator viewing. If one or more targets are identified in step 86, then the container is tagged or sorted in step 87 and an enhanced image is displayed in step 90 with a unique color or texture to identify the targets along with an appropriate text message to the operator.

The processing steps used to identify targets of interest are illustrated in greater detail in FIG. 6. A CT algorithm is applied to each of the spectral data sets in steps 101, resulting in multispectral attenuation data for each voxel comprising the object space. Calibration corrections are applied in step 102 to correct for the variation among detector elements and the calibration drift that occurs over time. This step may be performed before CT reconstruction, after, or both

depending on the level of real-time calibration required for the particular application. Use of a standard in the field of view generally requires the calibration correction be applied after CT reconstruction in order to determine the proper correction values. The fixed variation among detector elements resulting from imperfections in the manufacturing process on the other hand can be corrected before CT reconstruction by applying a correction directly to the signal output of each detector element.

After CT reconstruction and calibration correction, one spectral image is combined with another in step 103 to obtain relative attenuation data. This operation improves the signal-to-noise ratio of the resulting data. A matched filter is applied to the resulting data sets in step 104 to determine the statistical likelihood or probability of a match to targets of interest on a voxel-by-voxel basis. These data may be represented by the probability that a particular voxel contains a particular material determined by comparing the measured attenuation data with attenuation data previously measured for targets of interest. Because this comparison is made for each of several targets, each voxel may have several possible matches with varying levels of probability.

In step 105 contiguous or near contiguous voxels with similar matches are linked for further analysis beyond the voxel-by-voxel comparison of step 104. Shape, size, texture, and other characteristics of the data obtained from step 105 are matched to similar data representing targets of interest in step 106 to provide greater target discernment. In this way, the confidence level of a match is increased through the use of, for example, known shape, size, and texture qualities of the items to be identified.

In step 108 the relative attenuation data from step 103 is fused or combined to form a single image for operator viewing. This image is enhanced in step 109 with information from the analysis of steps 104-106. For example, highly correlated voxels can be illustrated in the image with a common color or texture to assist in operator viewing of the information. The results of the above analysis are displayed as a text message in step 107 and as an enhanced graphic image in step 110, which may be performed simultaneously on the same user interface screen.

Turning to FIG. 7, the processing of multispectral data to form an enhanced image with a greater signal-to-noise ratio is illustrated. Images 71-74 correspond to the five energy ranges discussed above. The images 70-74 contain three objects represented by a circle, rectangle, and triangle, and an artifact represented by a line. While the line appears uniformly in all five images 70-74, the other three objects appear with varying intensities. This simulates a key difference between actual objects in the scanned image and artifacts caused by the finite number of detector elements, the finite number of sources, defective detector elements, and similar limitations of the apparatus and processing methods. In many cases, the attenuation values of actual objects within

the scan space will vary with intensity level of the x-ray source while the artifact will have an attenuation value independent of energy level. The circle, rectangle, and triangle shown in images 70-74 simulate the variation of attenuation that different materials can have with varying x-ray source intensities. Thus, the circle is best resolved at the energy level of image 70, while the rectangle is best resolved at the energy corresponding to image 72 and the triangle at the energy level of image 74.

The fusing process in the present invention is used to both eliminate the artifact represented by the line in images 70-74 and to produce a single enhanced image 75 that includes a clear picture of all three objects. The first step in this fusing process is to subtract one of the images, say 71, from the other four images 72-74 to eliminate artifacts in the image data. Because the artifacts, as represented here by the line, do not vary in intensity from one image to another, this differencing technique effectively eliminates the artifacts from the resulting images. These four images are then summed to produce an enhanced image 75 that includes unique colors, numerical values, or other distinguishing qualities assigned to identify the objects. Since the multispectral data are collected electronically by the data acquisition circuit 3 of FIG. 1, this process is performed numerically in the present invention. The final image 75 may be used to display results to an operator and for subsequent processing, including shape, wavelet, fractal or other techniques of image data analysis.

A number of advantages of the present invention are evident from the above description. First, the invention provides a means and apparatus for automatic detection of concealed objects with or without operator involvement. Small quantities or features of a target of interest concealed within an object may be detected. The invention provides for high throughput of objects during scanning operations without compromising detection capability. CT data are obtained using a compact and stationary x-ray source and detector array. An enhanced x-ray image, CT image, or both are provided for operator viewing. Statistically based confidence levels for target identification may be used based upon the data stored within the system, and a continuous learning capability is provided for improving target identification with system use.

The foregoing description of specific embodiments of the present invention have been presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many modifications and variations are possible in light of the above teachings. For example, the number and arrangement of x-ray sources and detectors can vary considerably depending on the application. Where space constraints are not a factor, the sources can be moved away from the detectors resulting in greater coverage per source thus reducing the number of sources required. Also, the number and

sophistication of data processing steps can vary greatly depending on the target identification resolution needed for a particular application. CT processing, for example, may be unnecessary where objects in the scan plane are relatively thin and homogeneous. The same holds true for shape, size, and texture analysis: in some applications a voxel-by-voxel comparison will provide sufficient discernment capability, in other applications shape, size, or texture analysis may be required to meet target identification requirements.

The embodiments illustrated and described above were thus chosen to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following Claims and their equivalents.

I claim:

1. An apparatus for detecting targets of interest concealed within an object, said apparatus comprising:

an x-ray source for producing a beam of photons having an energy spectrum within a set band, said beam directed towards said object;

a photon energy absorbing detector array positioned opposite said x-ray source such that said object is located between said source and said detector array for measuring the energy attenuation of said photons after traveling along said beam path and through said object;

a data acquisition circuit responsive to said detector for forming attenuation spectral data from said photon energy measurements; and

means for analyzing said attenuation spectral data to identify targets of interest within said object.

2. An apparatus as recited in claim 1, wherein said data acquisition circuit includes a plurality of comparators and counters.

3. An apparatus as recited in claim 2, wherein said analysis means includes computed tomography.

4. An apparatus as recited in claim 3, wherein said analysis means further includes the application of calibration coefficients.

5. An apparatus as recited in claim 3, wherein said analysis means further includes a mathematical operation to form relative attenuation data.

6. An apparatus as recited in claim 3, wherein said analysis means further includes application of a match filter to compare measured attenuation values with those of said targets of interest.

7. An apparatus as recited in claim 5, including a means for fusing said relative attenuation data for display.

8. An apparatus as recited in claim 6, wherein said analysis means further includes the linking and analysis of voxels having similar attenuation values.

9. An apparatus as recited in claim 2, wherein said x-ray source is an L-shaped array comprised of a plurality of individual x-ray sources.

10. An apparatus as recited in claim 2, wherein said detector is an L-shaped array comprised of a plurality of individual x-ray detector elements.

11. An apparatus as recited in claim 2, wherein said x-ray source is a circular array comprised of a plurality of individual x-ray sources.

12. An apparatus as recited in claim 2, wherein said detector is a circular array comprised of a plurality of individual x-ray detector elements.

13. An apparatus as recited in claim 2, wherein said x-ray source is composed of a set of linear arrays, said linear arrays comprised of a plurality of individual x-ray sources.

14. An apparatus as recited in claim 2, wherein said detector is composed of a set of linear arrays, said linear arrays comprised of a plurality of individual x-ray detector elements.

15. An apparatus as recited in claim 8, including a means for teaching the system a new set of parameters to be used in subsequent target identification.

16. A method of detecting targets of interest concealed within an object, said method comprising the steps of:

generating a beam of photons having an energy spectrum within a set band, said beam directed towards said object;

measuring the energy level of said photons after traveling along said beam path and through said object;

forming attenuation spectral data from said photon energy measurements; and

analyzing said attenuation spectral data to identify target data within said object.

17. The method of claim 16, wherein said analysis step includes computed tomography.

18. The method of claim 16, wherein said analysis step includes the application of calibration coefficients.

19. The method of claim 16, wherein said analysis step includes mathematically combining one attenuation data set with another attenuation data set to form relative attenuation data.

20. The method of claim 16, wherein said analysis step includes the application of a matched filter.

21. The method of claim 20, wherein said analysis step further includes the linking and analysis of voxels having similar attenuation data.

22. The method of claim 19, further comprising the step of fusing said relative attenuation data to create an enhanced image for display.

23. The method of claim 22, wherein said enhanced image includes a unique display of identified targets to aid operator viewing.

24. The method of claim 21, further comprising the step of teaching the system a new set of parameters to be used by the system to identify new objects.

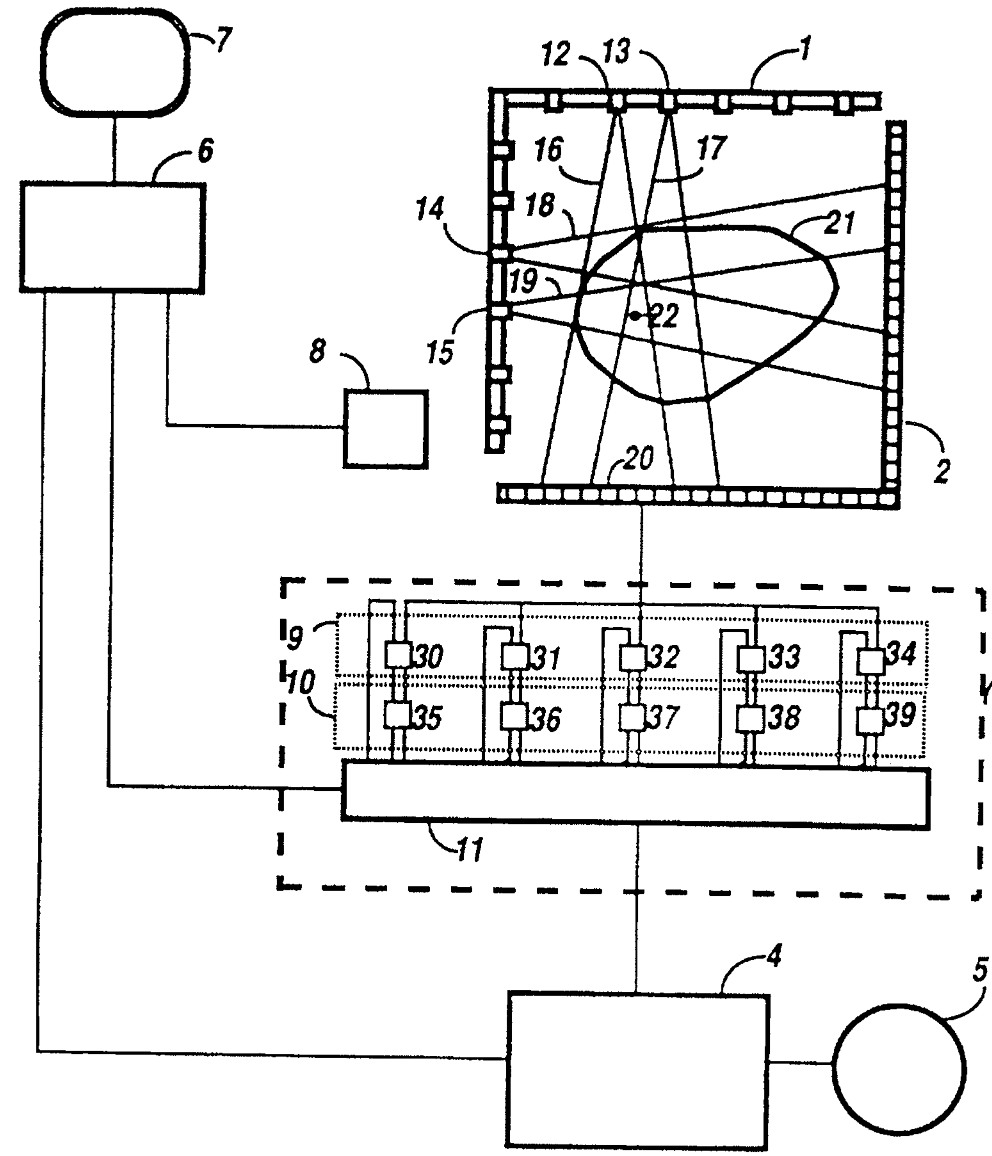

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FIG. 1

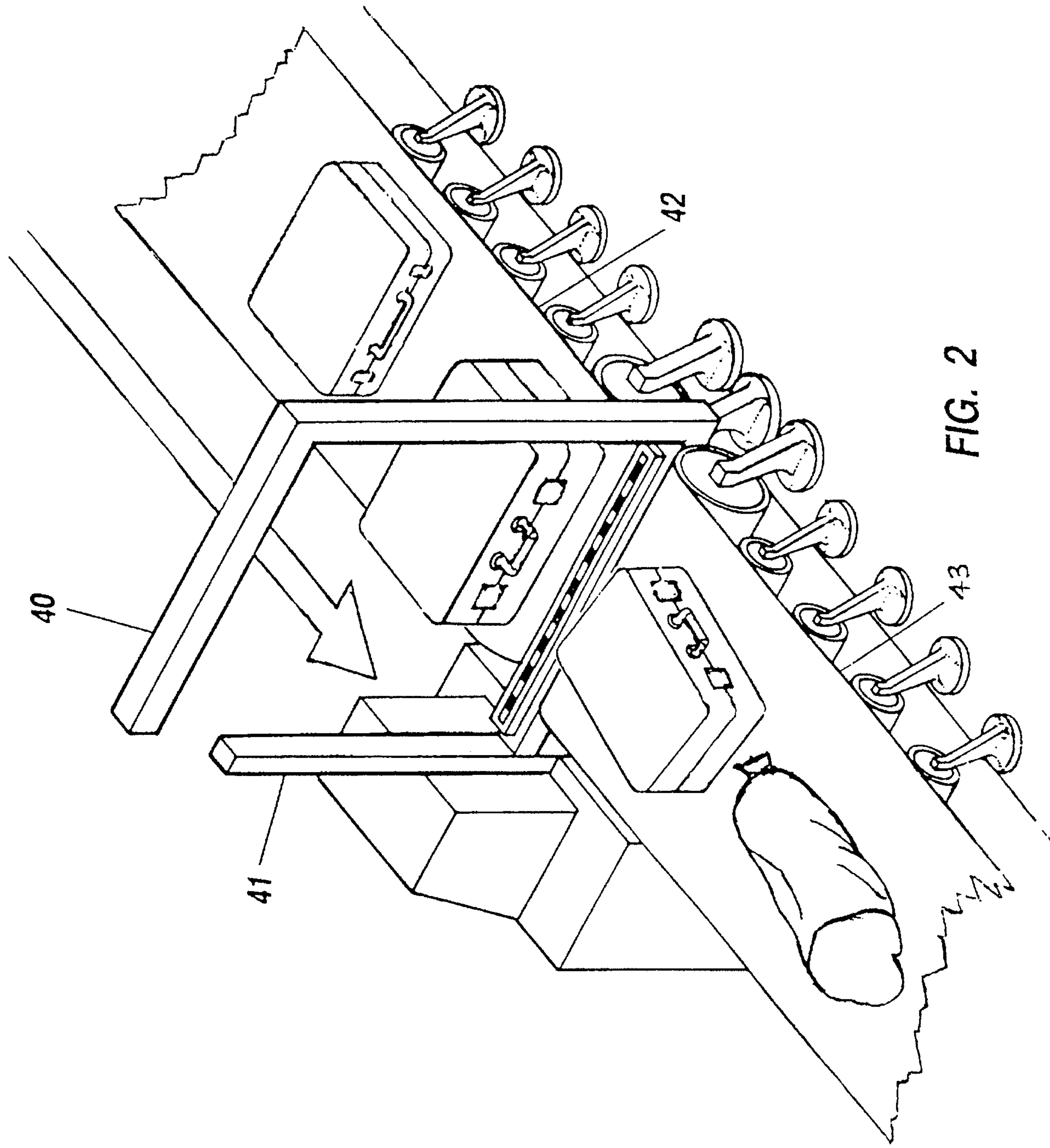


FIG. 2

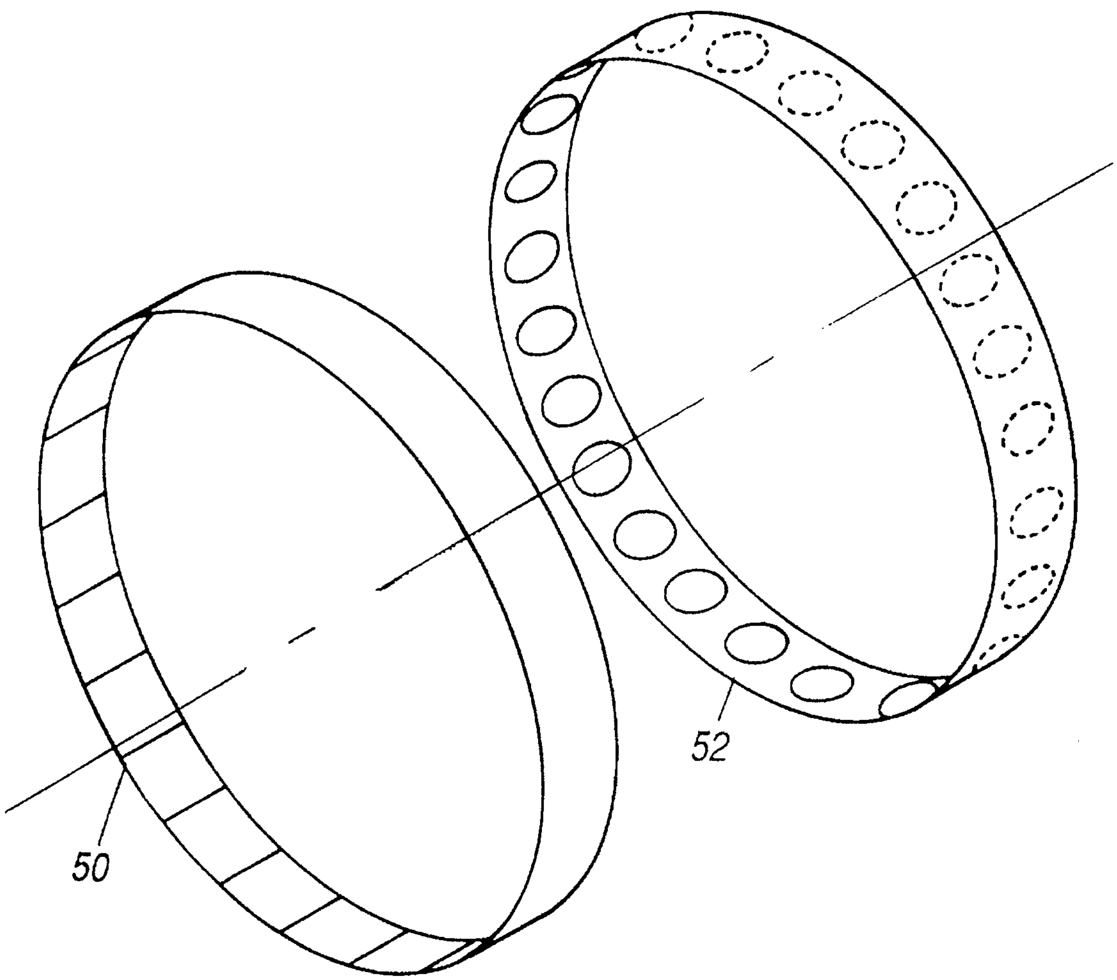


FIG. 3

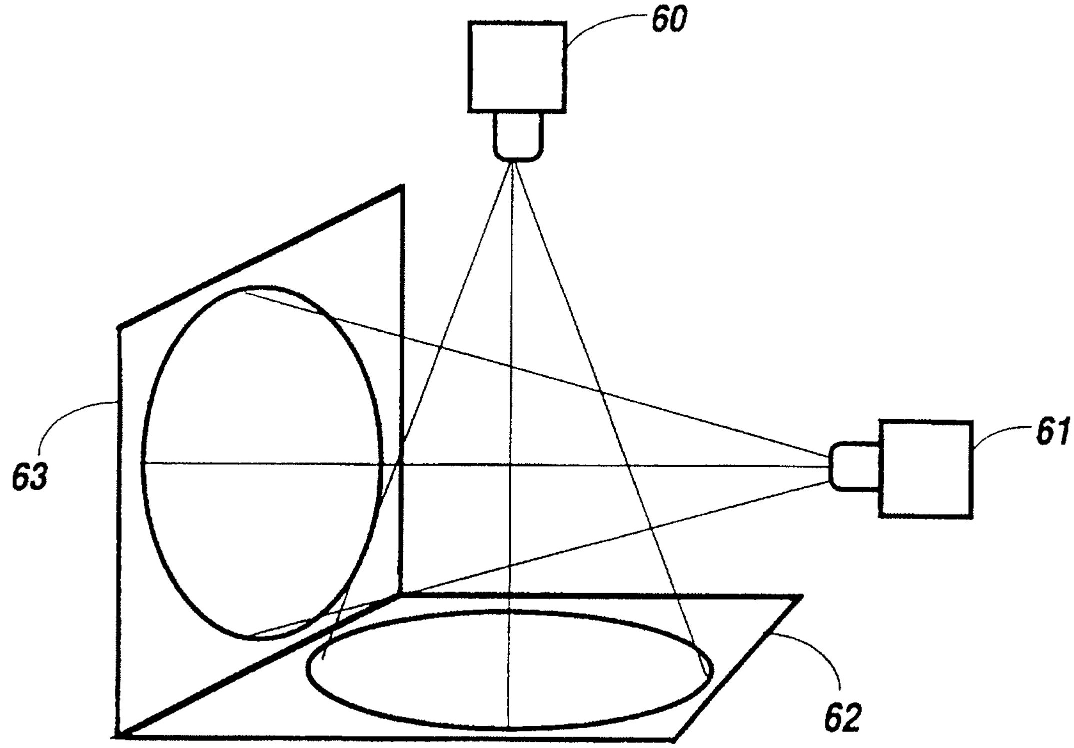
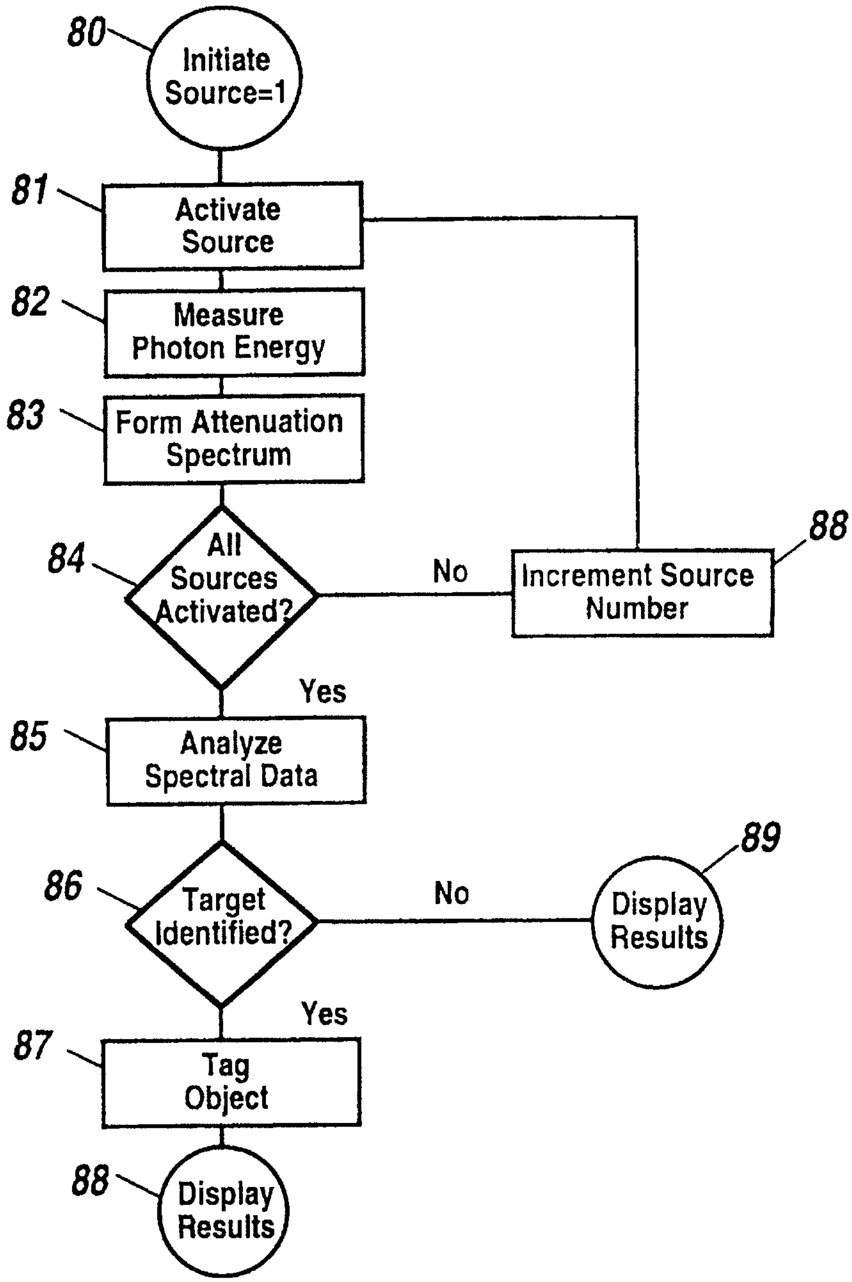


FIG. 4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Activate Source
82
Measure Photon Energy
83
Form Attenuation Spectrum
84
All Sources Activated?
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Increment Source Number
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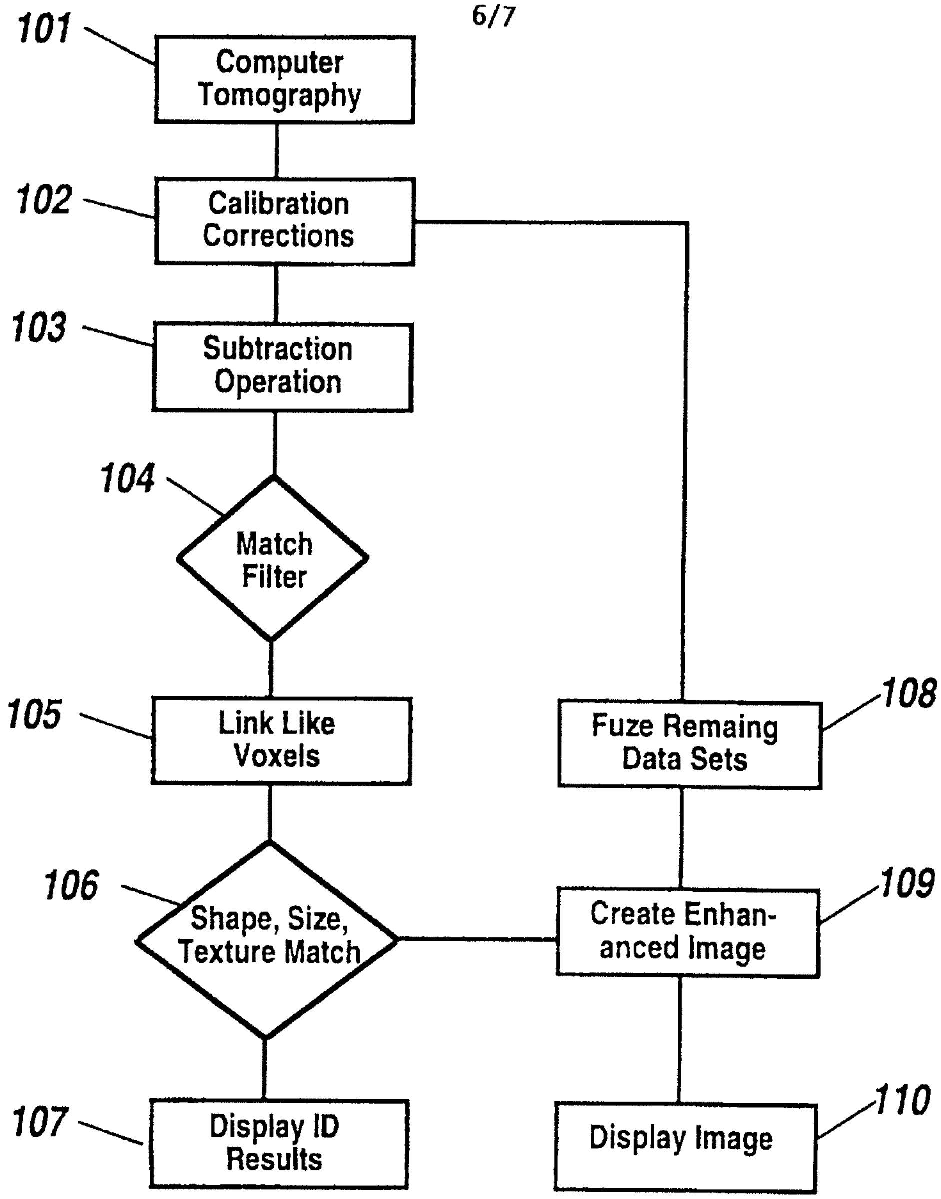
85
Analyze Spectral Data
86
Target Identified?
No
Display Results
89
Yes
87
Tag Object
88
Display Results

FIG. 5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Calibration Corrections
103
Subtraction Operation
104
Match Filter
105
Link Like Voxels
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Shape, Size, Texture Match
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Display ID Results
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Fuze Remaing Data Sets
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Create Enhan-anced Image
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Display Image

FIG. 6

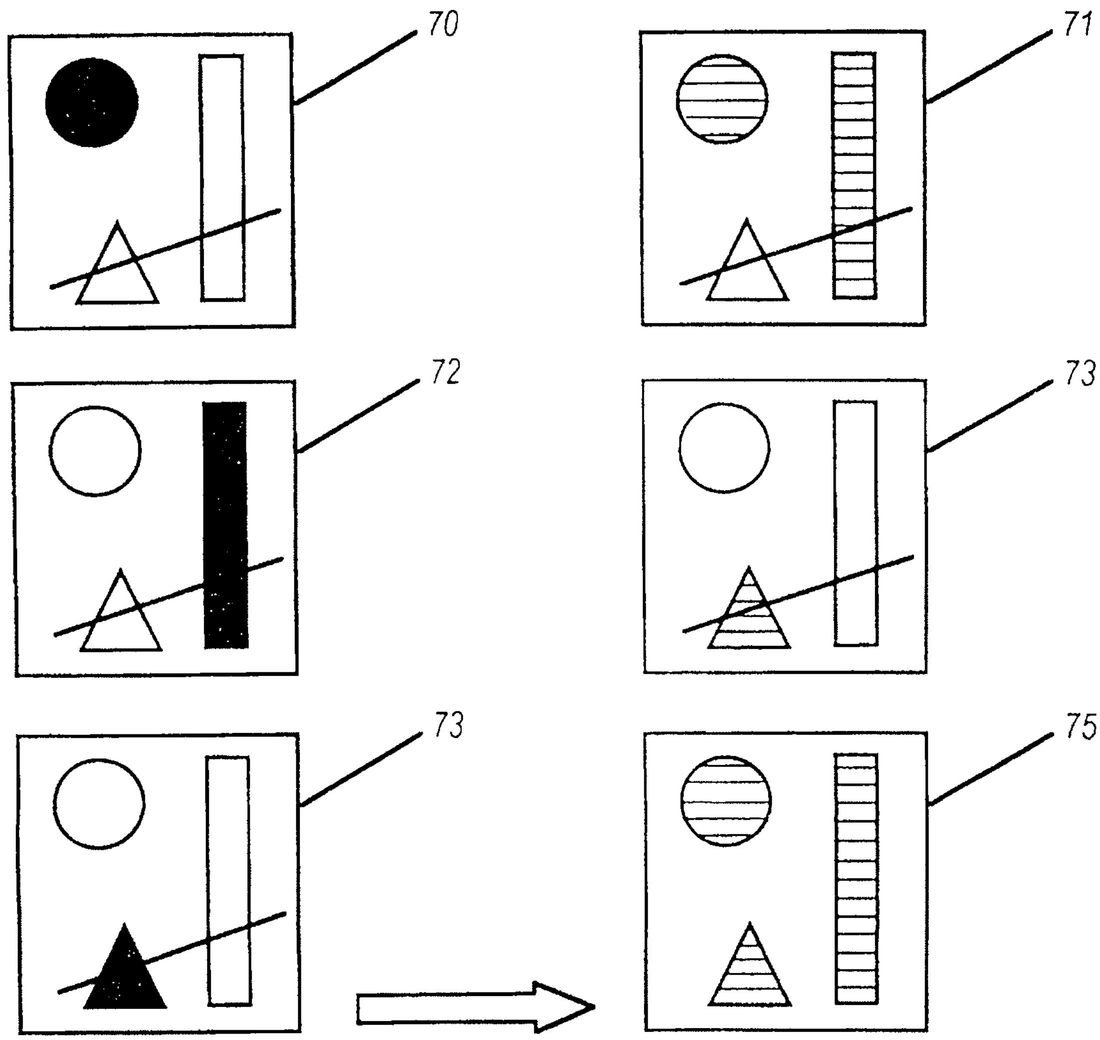

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/18200

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01N 23/04
US CL :378/57
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 378/57

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 4,651,005 (Baba) 17 March 1987 See the entire document.	1-5,16-19
Y		6-15,20-24
Y	US, A, 4,345,158 (Pfeiler) 17 August 1982 See the entire document.	9,13,14
Y	US, A, 4,759,047 (Donges et al) 19 July 1988 See the entire document.	10
Y	US, A, 4,239,972 (Wagner) 16 December 1980 See the entire document.	11,12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 JANUARY 1997	31.01.97

Name and mailing address of the ISA/US	Authorized officer
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